Characterisation of the mechanical behaviour of an unsaturated sandy silt
Caractérisation du comportement mécanique d'un limon sableux non saturé

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ABSTRACT: The results of an experimental study of the influence of the unsaturated state on the mechanical behaviour of a sandy silt are presented. After the characterisation of the saturated state behaviour, various paths of stress and suction under triaxial, oedometric and isotropic conditions are investigated. Complementary experiments made in the two institutions (EPF Lausanne and University of Liège) are shown.

RESUME: Cet article présente une étude expérimentale de l'influence de la non-saturation sur le comportement mécanique d'un limon sableux. Après avoir caractérisé le comportement du sol à l'état saturé, on étudie la réponse du matériau sur des chemins isotropes, oedométriques et triaxiaux pour différents états de contrainte et de succion. Des essais complémentaires des deux institutions (EPF Lausanne et Université de Liège) sont présentés.

1. INTRODUCTION

A whole class of geotechnical problems is conditioned by the unsaturated behaviour of soils (which we define as the state where the pore water-pressure is negative- with soil mechanics sign convention: compression positive). This condition appears in the construction of embankments, stability of tunnels, loading of road foundations and environmental engineering. The unsaturated state can also be due to a natural cause: infiltration and evaporation phenomena.

In this paper we present a hydro-mechanical study of the behaviour of a remoulded sandy silt. This soil is submitted to mechanical loading at different initial suctions (excess of pore air-pressure to water-pressure) and to hydric loading (variation of fluid pore pressure) at different initial mechanical stresses.

We consider that two stress-state variables govern the unsaturated soil behaviour, namely:

(i) the net mean stress p*, spherical part of the net stress tensor

$\sigma_{ij}^* = t_{ij} + p^*\delta_{ij}$ (1)

where t_{ij} is its deviatoric part and δ_{ij} is the Kroneker delta with

$p^* = p - u_a$ (2)

where p is the mean total stress

$p = \sigma_{ii} / 3 = (\sigma_1+\sigma_2+\sigma_3) / 3$ (3)

and u_a the air pressure

(ii) the matrix suction s,

$s = u_a - u_w$ (4)

with u_w the pore water pressure.

This hypothesis is one of the cases proposed by Fredlund and Morgenstern (1977) in which they show that the total stress $\boldsymbol{\sigma}$, the pore air-pressure u_a and the pore water-pressure u_w can be combined in two independent stress parameters in order to correctly describe the mechanical behaviour of unsaturated soils.

2. EXPERIMENTAL APPARATUS

The saturated tests were made in standard triaxial and oedometer apparatus. The same equipments were adapted to run unsaturated tests. Two different techniques were used to impose suction: the air-pressure method (EPFL) and the osmotic method (Uni. Liege).

The first one (Figure1a) is based on the axis-translation technique (for details see Fredlund & Rahardjo, 1993). The air-pressure is imposed at the top of the sample. The pore water-pressure is measured or imposed at the bottom, where there is a special high air entry value ceramic. Three apparatus were adapted for this technique: a standard triaxial, an oedometer and a Richards cell (pressure plate extractor).

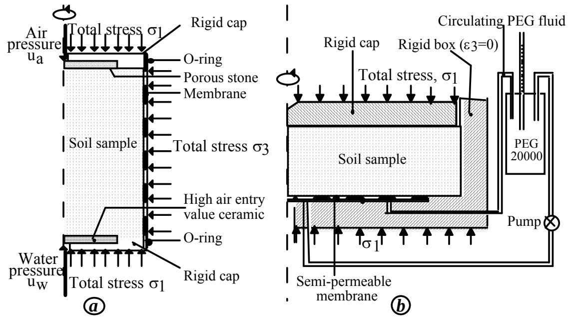

Figure 1. a) Imposed air-pressure technique (EPFL)
b) Osmotic technique (Uni. Liège)

The osmotic technique (Figure 1b) was used on an oedometer. It is based on the use of a semi-permeable membrane and a macromolecular solution (polyethylene glycol 20000). The sample is in contact with the membrane and the solution is moving behind. The soil water is attracted by osmosis to the solution until equilibrium is reached between the capillary suction in the sample and the osmotic suction. The value of suction depends on the concentration of macromolecular solution (Suraj de Silva, 1987).

In both techniques the equilibrium state, for a given suction is supposed reached when the water volume variation tends to zero. Generally this state is obtained in 15 days for a suction of 100 kPa and in 25 days for a suction of 200 kPa (Laloui *et al.*, 1995).

3 SAMPLE PREPARATION

The soil used is a washing sandy silt from the region of Sion (Switzerland). Its characteristics are given in Table 1.

The sample preparation was done in the aim to be as close as possible to the mechanical and hydric virgin states. The procedure consists in mixing a dry soil with de-aired and demineralised water to obtain a water content (w) value equals to 1.5 times the limit of liquidity (w_L). This value was found to guaranty an initial saturated state. Then the sample is put in its looser state (initial void ratio

Table 1: Characteristics of the Sion silt

w_L (%)	w_P (%)	I_P	%< 2μm	%< 20μm	%> 60μm	γ_s (kN/m^3)
25.1	18.8	6.4	6.4	40.7	22.3	27.35
±0.3	±2.1	±2.3	±2.3	±0.8	±2.3	±0.06

$e_o \approx 0.9$) in the Richards cell. For the triaxial apparatus we give a shape to the sample inside a moulding-tube with a small load (Ko consolidation with a small preconsolidation pressure around 30 kPa). After this phase the void ratio is between 0.6 and 0.7.

4. HYDRO-MECHANICAL PATHS

The different types of stress path are summarised in Figure 2. σ_1 and σ_3 are the principal vertical and lateral stresses. In the following, we call *mechanical* path a path obtained by applying a total external stress σ_1 or σ_3, while we call *hydric* path a path obtained internally by modifying either u_a and u_w. We suppose that the hydric effect is only isotropic.

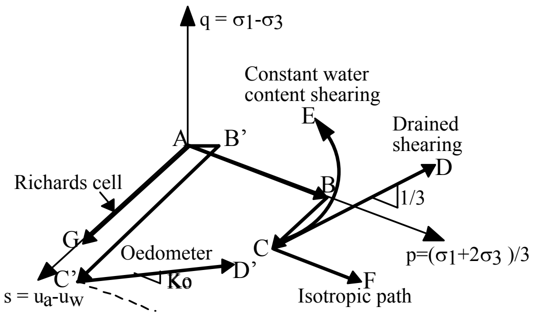

Figure 2: Hydro-mechanical stress paths

For the *triaxial tests* the samples are first consolidated to a given confining pressure (A-B) in saturated conditions. This should erase all the mechanical history of the sample as the confining pressure is always higher than the preconsolidation pressure of the soil. Then, in an unsaturated test, the sample is submitted to an hydric path (B-C): the suction increases with the application of u_a, while keeping u_w equal to the atmospheric pressure. Finally, when the equilibrium is reached (point C), several stress paths are analysed:

1- C-F : **isotropic**. This path is obtained by increasing the confining pressure p while keeping both u_a and u_w constant (this allowing free flow of air and water).

2- C-E : **constant water content shearing**. This path is driven in water undrained conditions while maintaining a constant air-pressure u_a. The water-pressure u_w is measured during the shearing, so that the suction is known.

3- C-D: **drained shearing test**. It consists in increasing the deviatoric stress while keeping both u_a and u_w constant.

The *oedometric* unsaturated path (A-B'-C'-D') was done with the osmotic method. The samples were preconsolidated isotropically at about 300 kPa during the preparation. They are submitted to a very small loading (point B', 12-20 kPa) to ensure a good contact between the sample and the cell basis). Then there is a drying path (B'-C') where the sample is submitted to a given suction. Finally this suction is kept constant, while the vertical stress is increased by steps (C'-D') in oedometric conditions.

The aim of the last path (A-G) is to drive *hydric* paths without any "mechanical" stress. The sample's own-weight is supposed negligible. For each suction level at least four samples are prepared. At equilibrium two samples are used to determine the water content and two for the volume measure.

To determine the volume, the samples are put in petroleum. By this way only the air pores are filled with this liquid, as the hydrocarbons are hydrophobic. Then the volume can be measured classically with a pycnometer (Geiser *et al.*, 1996).

5. RESULTS AND INTERPRETATIONS

A series of 47 tests were performed at EPFL and 17 at Uni. Liège. The main results on different paths are given in this chapter. Note that the range of degree of saturation Sr remains between Sr=100% and Sr=50%.

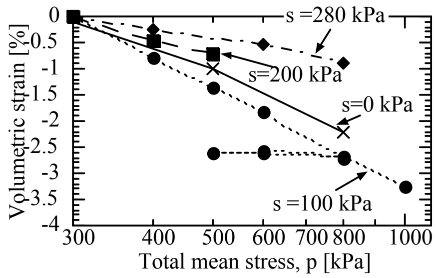

Figure 3: Evolution of the volumetric strain at different constant suctions.

5.1 *Isotropic and oedometric mechanical behaviour* (C-F; C'-D')

Figure 3 shows the evolution of the water-volumetric strain (water volume change divided by the total volume) versus the net mean pressure p* in isotropic conditions. The tests (path C-F) were done at four different constant suctions: 0, 100, 200 and 280 kPa, after a saturated isotropic consolidation (path A-B) at 300 kPa. The results show that the mechanical compressibility in unsaturated conditions decreases with increasing suction.

The variation of the void ratio with the suction under oedometric conditions shows globally the same kind of compressibilities' evolution (Figure 4). This result is obtained with the following constant suctions (point C'): 0, 50, 100, 200 and 300 kPa.

In the saturated case (Figure 4) this silt shows an increase in mechanical compressibility with the mean pressure for the experimented stress range. As a consequence, two distinct compressibilities (slopes in the e-lnσ_1 diagram) are chosen for two different ranges of stresses: λ_1 for a vertical stress σ_1 between 100 and 400 kPa and λ_2 for σ_1 higher than 400 kPa.

Figure 5 shows that the compressibilities of the soil decrease with the suction, as for example:

For s=0 kPa, λ_1=0.032 and λ_2=0.047

For s=200 kPa, λ_1=0.020 and λ_2=0.028

The elastic compressibility κ corresponds to the unloading slope. It can be considered as independent from the suction (Figure 5). The value of κ is around 0.007.

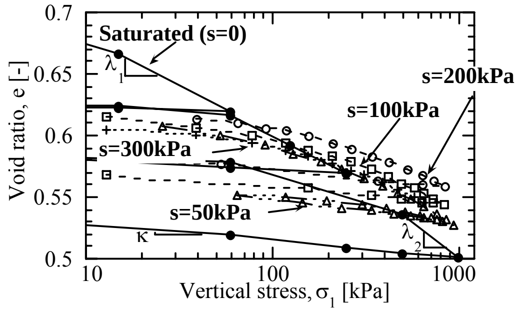

Figure 4: Evolution of the void ratio at different constant suctions.

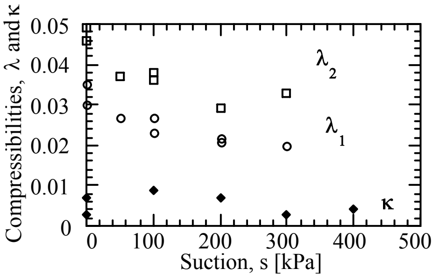

Figure 5: Evolution of the compressibilities with the suction.

These results are compatible with the feature proposed by Alonso *et al*. (1990), who suggested that κ was not dependant of the suction, and that λ decreases with the suction before to tend towards an asymptotic value. However 2 or 3 more points would be needed to clearly determine this asymptotic value.

5.2. *Deviatoric mechanical behaviour*

Constant water content shearing tests (path C-E)

The shear rate during the constant water content tests was of 0.06 mm/min. Two ranges of stresses were analysed:
- tests with moderate initial mean stresses (200-300 kPa): Figures 6&7.
- tests with a large initial mean pressure of 1000 kPa and small suctions: Figure 8.

Figure 6 and further interpretation show an increase of strength and stiffness with increasing air-pressure and suction. The unloading modulus seems to be independent from the suction. Concerning the volumetric behaviour, one can observe a tendency to dilatancy when the air-pressure increases. There is less generation of pore water-pressure with increasing suction, due to the smaller degree of saturation.

The same feature can be observed on Figure 7 corresponding to 300 kPa lateral pressure. However, when the net initial mean pressure is small (p*=100 kPa for u_a=200 kPa and p*=20 kPa for u_a=280 kPa), cinematic failures occur. The initiation of such a softening effect is a function of the degree of saturation.

A different behaviour is observed on the Figure 8a for tests with a large initial mean pressure (1000 kPa). All unsaturated samples give almost the same peak strength, which is higher than for the saturated case. The ultimate resistance seems to be the same for the saturated and unsaturated cases. This result of no significant effect of the suction on the ultimate resistance for a large net mean stress was also observed on collapsible silt (Maâtouk, 1993) and compacted silt (Delage *et al.*, 1987). In the volumetric plane, the Figure 8b shows that the same pore water-pressure is obtained for all unsaturated tests. They have less contractant behaviour than in the saturated case.

Drained shearing tests (path C-D)

The shear rate during the drained tests was 1.5 μm/min. This rate was determined via the classical Gibson and Henkel method (1954):

$$t_f = H^2 / (h * c_v * (1 - U_f))$$

where t_f : time required to fail the sample
H : half high of the sample (50-55 mm)
U_f = the average degree of dissipation of the induced pore-water pressure at failure. Generally 0.95 is assumed to be enough to find the soils intrinsic characteristic in drained conditions.

We deduced the coefficient of consolidation c_v from the isotropic unsaturated tests (Geiser *et al.*, 1996). This method has the advantage of including directly the drainage conditions as well as the relative permeability of the silt and the high air entry ceramic for different suctions and mean pressures.

Figure 9 shows two unsaturated tests with the corresponding saturated case at two different confining pressures (400 and 600 kPa) and for a suction of 100 kPa. The comparison of the saturated and unsaturated cases at the same mean pressure shows almost the same friction angle, stiffness and unloading modulus. Nevertheless the volumetric behaviour is clearly different for saturated and unsaturated states. The water content of the unsaturated samples seems continuously decreasing and one cannot see a clear stabilisation level. This confirms the constant water content shearing tests results showing the influence of the suction on the volume changes.

Evolution of the critical state

As the water content of the unsaturated samples cannot reach a stabilisation when the axial deformation tends to a large value, we defined in a first approximation the critical state as the state where there is no more change in the deviatoric stress for large axial deformation. In the following interpretation we did not take into account the tests which failed during the shearing. Figure 10 shows the critical state points of all drained and undrained tests in the p* vs. q plane.

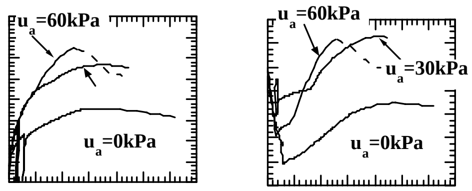

Figure 6: Constant water content tests σ_3=200 kPa.

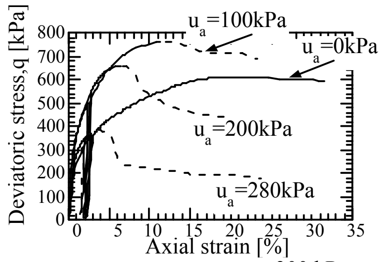

Figure 7: Constant water content tests σ_3=300 kPa.

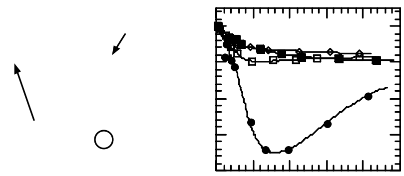

Figure 8: Constant water content tests σ_3=1000 kPa

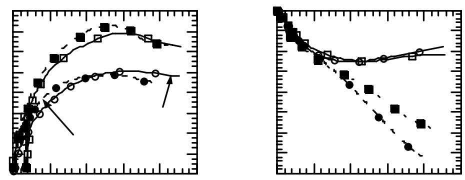

Figure 9: Drained shearing tests at two different confining pressures.

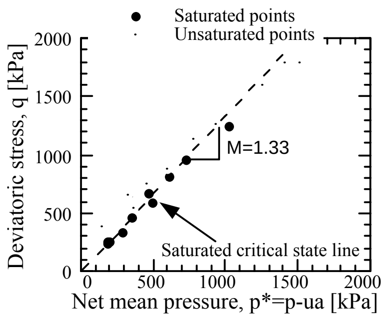

Figure 10 : Evolution of the critical state with the suction.

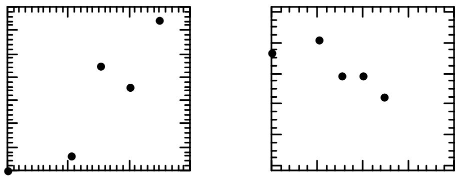

Figure 11: Evolution of the friction angle and cohesion with the suction.

Until a net mean pressure of 1 MPa, all unsaturated points are above the saturated critical state line q=Mp* (dotted). Figure 11 shows the evolution of the slope of the critical state line M and the cohesion c (value of the deviatoric stress at p*=o) with the suction. From those results we deduced that the critical friction angle ϕ_{pp} decreases with the suction while the cohesion increases as for example:

$\phi_{pp} = 33°$ at s = 0 kPa; $\phi_{pp} = 26°$ at s = 125 kPa
c = 0 kPa at s = 0 kPa; c = 320 kPa at s = 125 kPa
The same tendencies were observed on collapsible silt (Maâtouk, 1993) and compacted silt (Delage *et al*., 1987).

This result of simultaneous variation of the critical slope M and the cohesion c gives a good representation of the shearing strength evolution with suction. We can also conclude that the unsaturated states lead to very different volumetric behaviour than in saturated conditions.

5.3 Hydric behaviour (A-G)

The results of the hydric tests obtained in the Richards cell are shown in the Figure 12 (a, b, c, d, e).

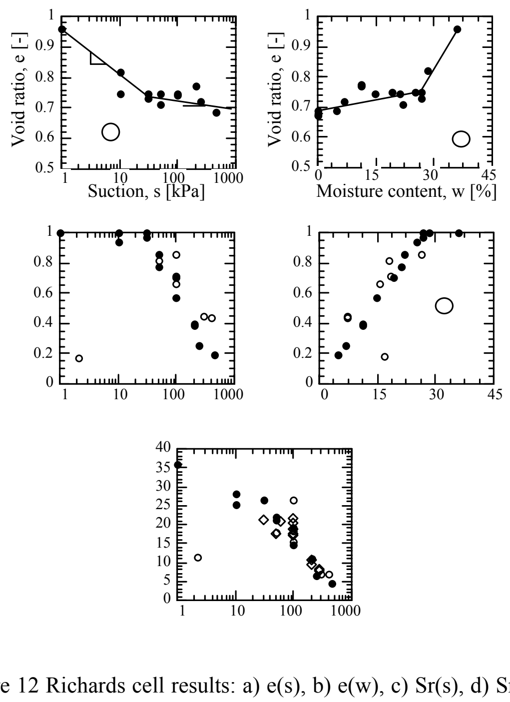

Figure 12 Richards cell results: a) e(s), b) e(w), c) Sr(s), d) Sr(w), e) w(s)

Principally Figures 12c and 12d show that the air entry value is at a suction of 30 kPa. It means that this silt remains saturated below this value. We can also notice that there is a residual degree of saturation around 0.2 (Figure 12c). On the Figure 12-a, we notice that the suction has the same type of influence as a mechanical stress, but with different compressibility slopes: λ_s=0.06 and κ_s=0.009. As long as the sample is saturated (s<30kPa) the void ratio decreases highly with suction (note that the hydric compressibility λ_s is higher than the mechanical one λ). Then for suction exceeding 30 kPa the void ratio remains almost constant and the degree of saturation is highly affected by the suction variation (Figure 12c). The same observations can be done for the graph 12b representing the evolution of the void ratio with the moisture content. On Figures 12c to 12e, we added the results deduced from the hydric paths (B-C, B'-C') in the other tests: triaxial and oedometer. The points are very close to the one found in the Richards cell. It seems that the hydric behaviour of the silt defined by λ_s and κ_s is not affected by the initial void ratio.

6. CONCLUSION

An understanding of the behaviour of unsaturated soils is important for the design and analysis of geostructures. The main effects of suction on the behaviour of a remoulded soil are analysed.

All these experimental results on a remoulded sandy silt constitute a good database for further developments and for the validation of constitutive model taking in account an unsaturated state. A first attempt as a joint work between EPFLausanne and Uni. Liège is given in the same Proceedings (Charlier *et al.*, 1997).

For the mechanical behaviour, the results show that the compressibility globally decreases with the suction, while the unloading compressibility stays almost constant. The triaxial tests reveal informations about the evolution of the critical state parameters: the friction angle decreases and the cohesion increases with increasing suction.

The hydric drying paths were principally analysed with the Richards cell. They give a complete determination of the evolution of the degree of saturation, void ratio and moisture content with the suction. This is a good base for further evolution equations.

7. ACKNOWLEDGEMENTS

All test results presented in this paper were obtained at the EPFLausanne, except Fig. 4, 5 and part of 12c-e obtained at Uni. Liège. The work at EPFL is supported by part by the Swiss NSF, grant 21-42360.94, and by the Swiss OFES, grant 94.0150. Uni. Liège thanks the CE who supported its collaboration through its membership in the ALERT Geomaterials network.

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